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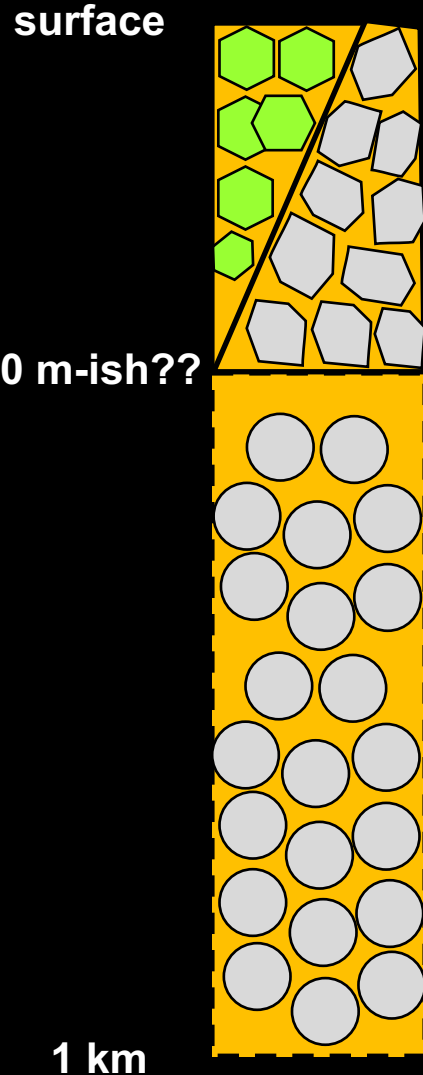
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Cryovolcanism in Icy Ocean Worlds: Perspective from Models of Radial Structure

Titan subsurface: The first 1 km

Speculative structure – need better estimates and constraints

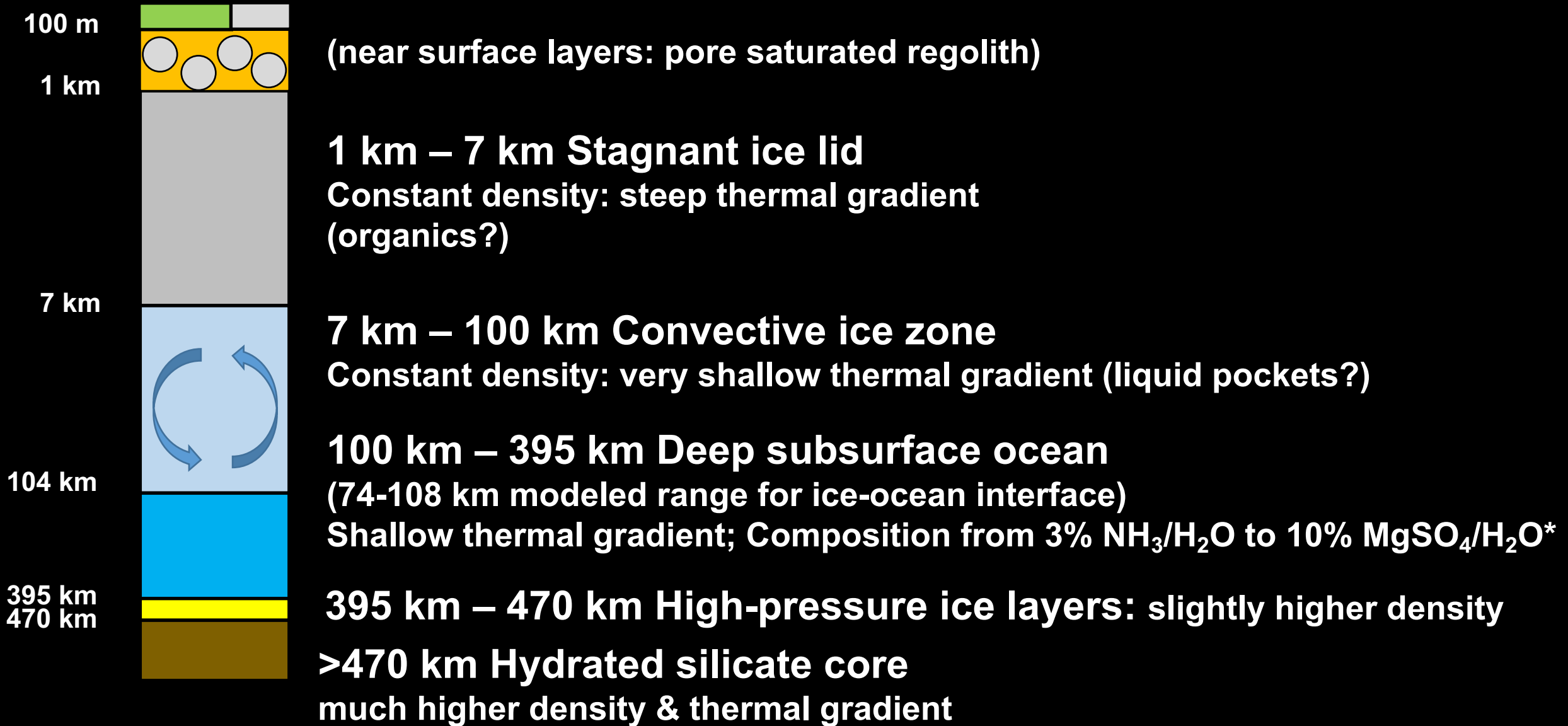


surface– 100 m: organic deposit depth – spatially variable depths
Possibly liquid hydrocarbon saturated (Hayes et al. 2008, Liu et al. 2016)

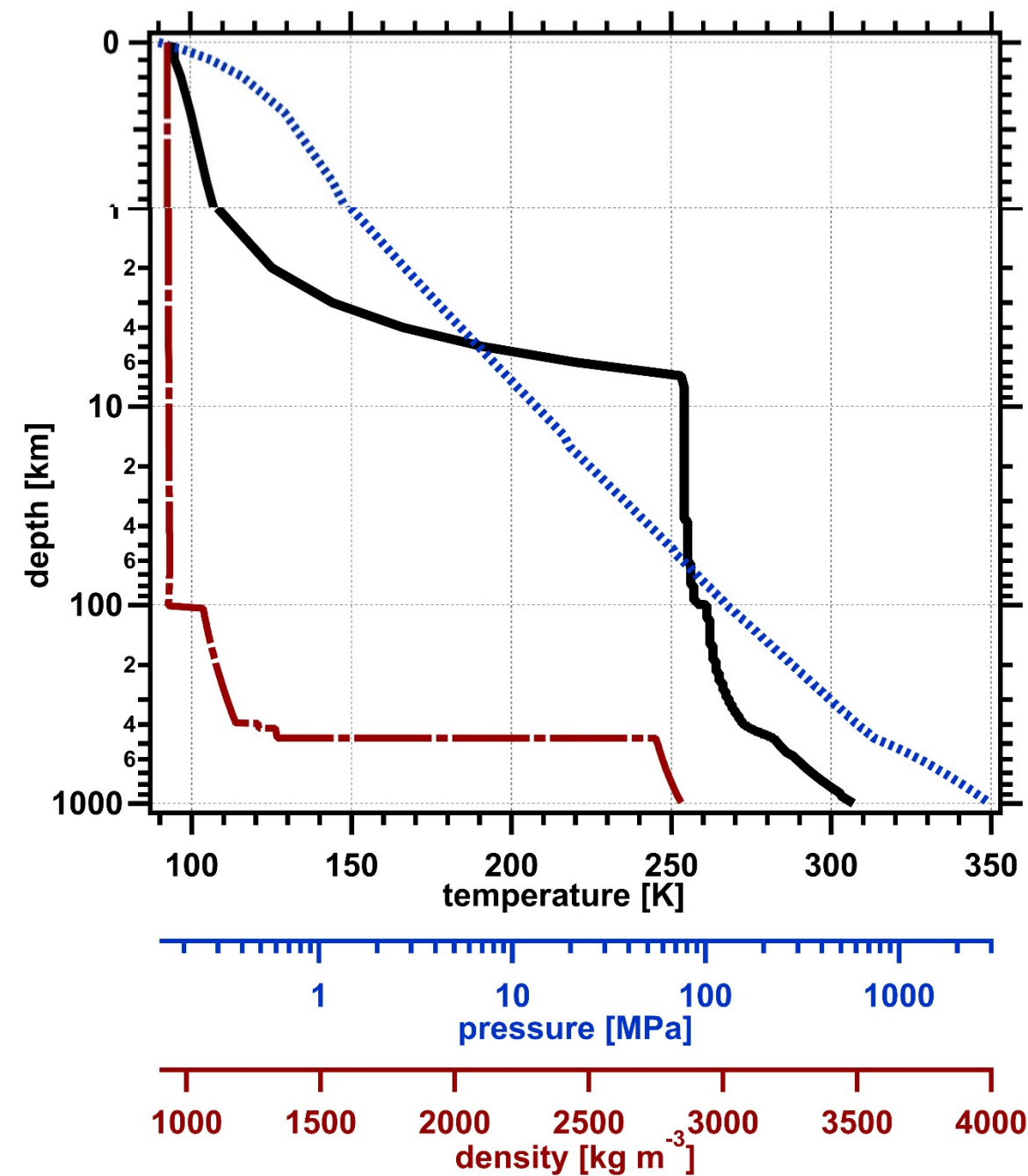
100 m – 1 km: Hydrocarbon (ethane?)-saturated regolith
From 10 m ethane accommodated in 5% void areas in regolith → 200 m-ish.
How deep do organics penetrate from surface?
Fluids with dissolved material?
Clastic materials?

>1 km: Mostly H₂O / clathrate?
(e.g., Sohl et al. 2010, Choukroun and Sotin 2012)

Titan deep subsurface: 1 km – 1000 km



*Based on *Cassini* gravity science data and modeling in Vance et al. 2018



surface
10 m

7 km

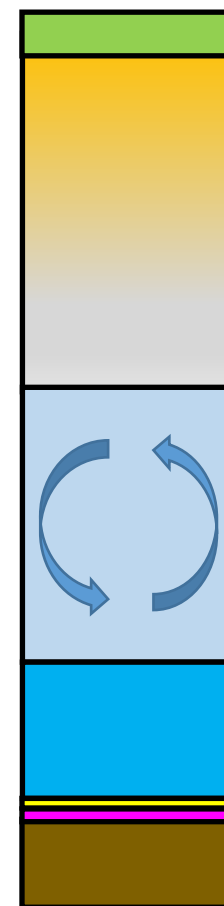
104 km

395 km

420 km

470 km

1000 km
and deeper



0-100 m Surface organics

100 m – 7 km Stagnant ice (Ice 1h) lid with Pore-saturated organic liquids in upper regions. Clathrates also possible.

7 km – 100 km Convective ice (Ice 1h) zone
Some liquid concentrated pockets possible?

104 km – 395 km Deep liquid water ocean

395 km – 420 km High-pressure ice (Ice V)

420 km – 470 km High-pressure ice (Ice VI)

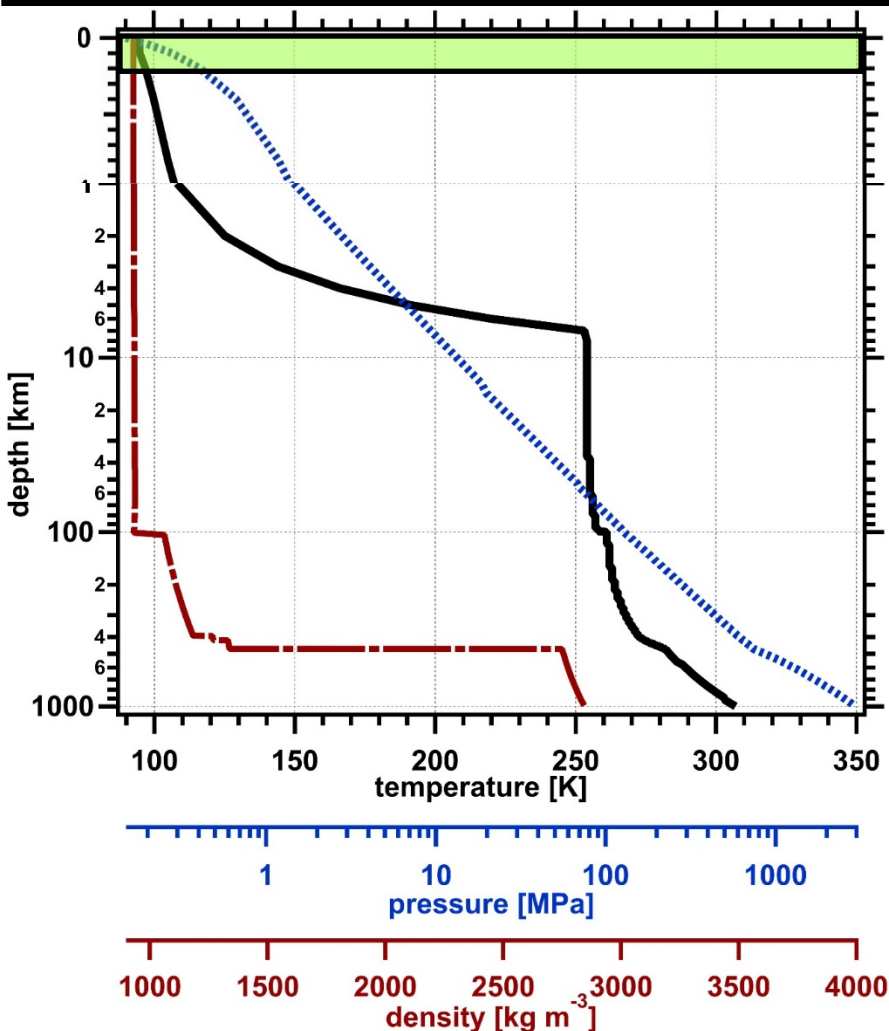
470 km → Center hydrated silicate core

Titan modeled T, P , and density

Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

data from Vance et al., 2018

Surface – 100 m Surface organics layer



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Organic airfall deposit

Processed geology: eolian, erosion, dissolution
Likely methane saturated: wet dry cycles

$T = 90 - 95 \text{ K}$

$P = 0.15 \text{ MPa}$

Density: organic, so 0.9 g/cm^3

Kinetically inhibited reactions - sloooooooooow
Physical (geology) movements >> biology
("Hey, I was gonna eat that!")

Cryogenic methane is a poor solvent

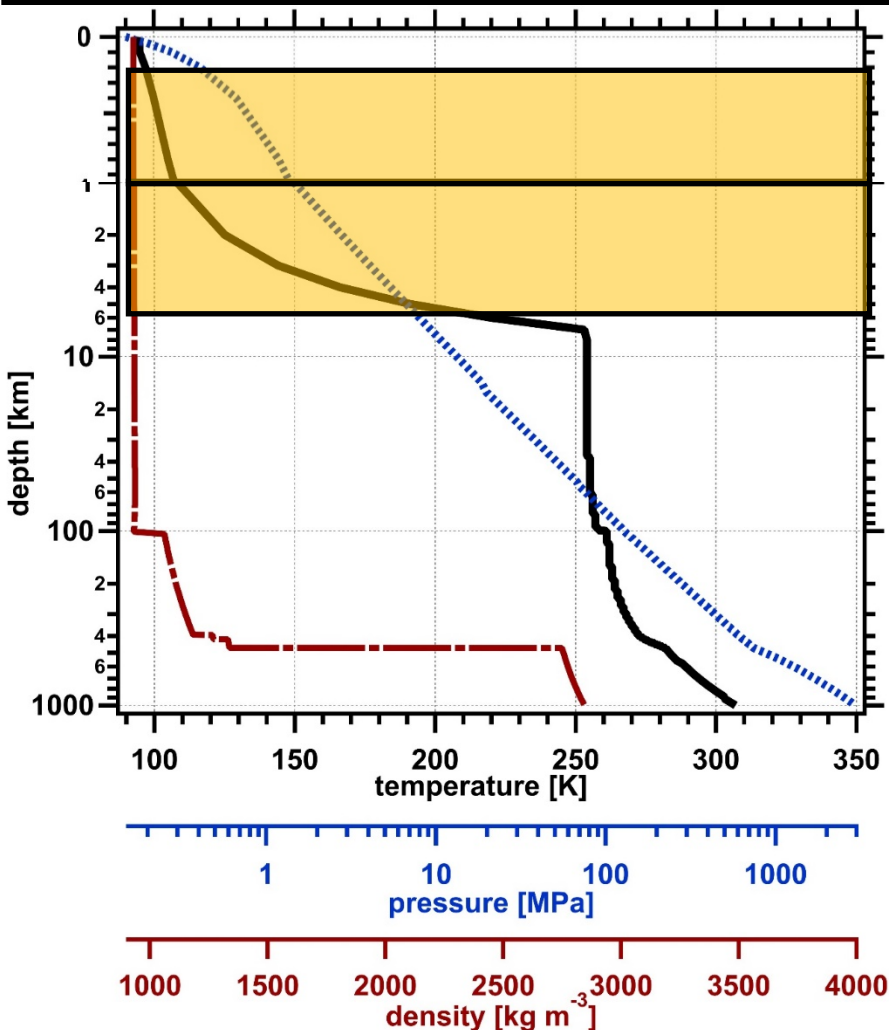
Building bigger molecules makes them insoluble!

(Life would require weak/transient, not covalent bonds)

Key questions:

What are typical dominant organics at surface?

100 m – 7 km Stagnant ice lid



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Hydrocarbon saturated ice (Ice Ih) zone

Porous (ice Ih) regolith? Possible clathrate ice.
Some organic penetration from tectonics, hydrocarbon fluid circulation

T = 95 K – 253 K steep thermal gradient

P = 0.15 MPa – 10 MPa

Density: 0.93 g/cm³

Warmer, better hydrocarbon solvents? ethane, propane

Some organics transported by fluid flow?

Cryovolcanic emplacements on ascent?

Crater impact mixing / injection

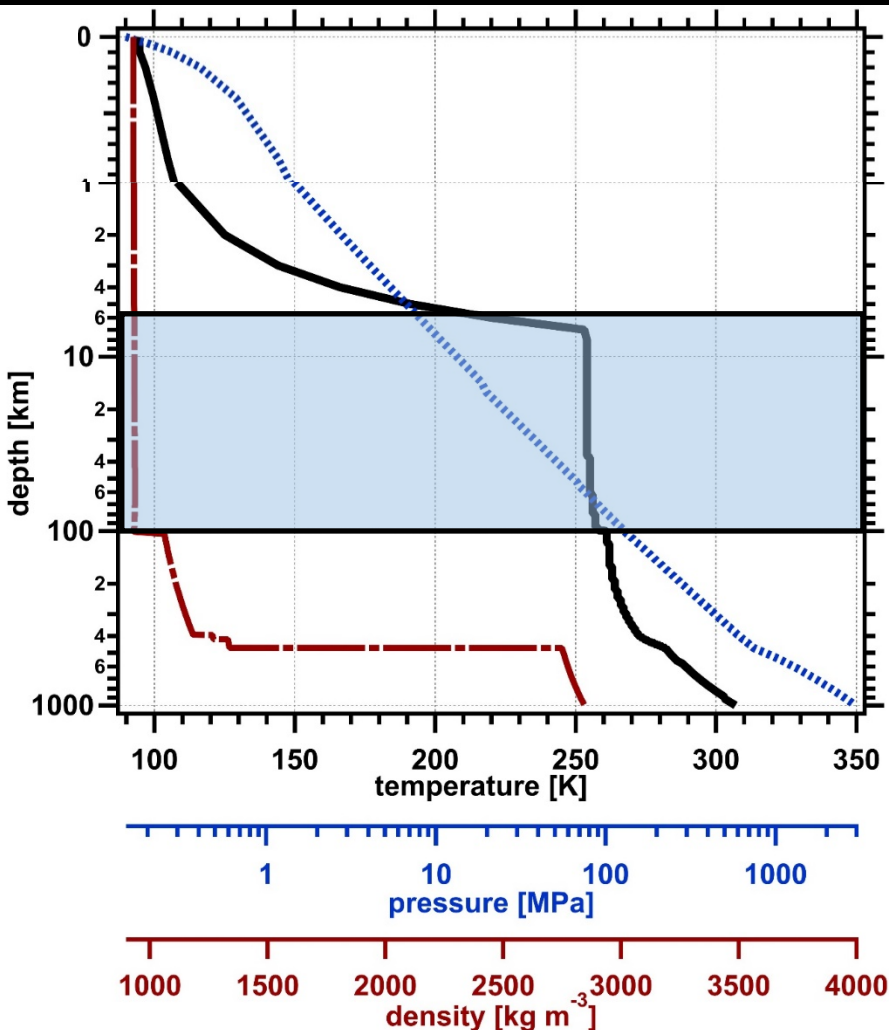
Key questions:

How deep do hydrocarbon liquids go?

How deep are organics (dissolved?) transported?

What are downward transport mechanisms/fluxes

7 km – 104 km Convective ice zone



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Conveying warm ice zone

“conveyor belt”

Liquid water may occur in the ice (Kalousova et al. 2014)

$T = 253 \text{ K} - 261 \text{ K}$ shallow thermal gradient

$P = 10 \text{ MPa} - 130 \text{ MPa}$

Density: 0.93 g/cm^3

Organics descending!

Jacked liquid salt water solutions from upwelling!

Mixing of solid water/organics/liquids! Wheee!

Steep thermal gradient at ice-ocean interface

Key questions:

What are freezing points of relevant salt solutions at pressure?

What is limit for ascending liquid water solution?

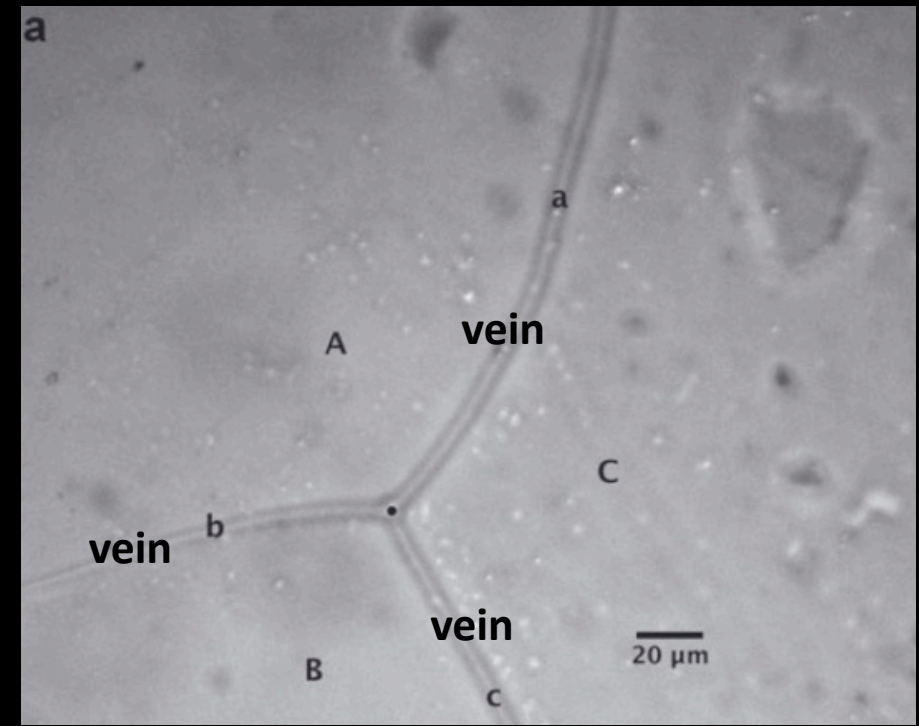
What terrestrial life could exist in these conditions?

Chemical concentration

As ice grains freeze out chemical concentrates

Data from GISP 2 ice core at 146 m depth

<u>ion</u>	<u>bulk</u>	<u>vein</u>	<u>Conc. factor</u>
Sulfate	0.26 μM	101 mM	200,000
Nitrate	0.89 μM	53.6 mM	400,000

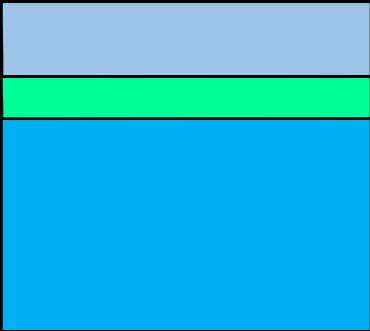


GISP 2 ice core 146 m depth image
Vein structures shown

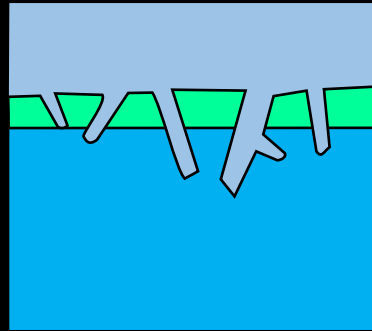
Huge increase in local ion concentrations in ice veins
Potential chemical microenvironments
10 – 100 μL volume per L of bulk ice volume (1 ppm)

Titan ice-ocean interface:

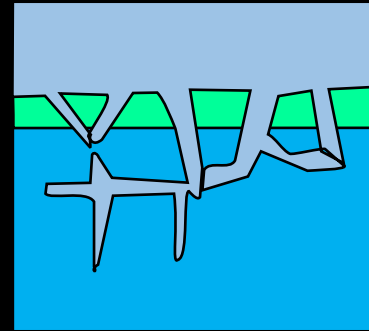
Convecting ice interface could make diverse isolated chemical environments



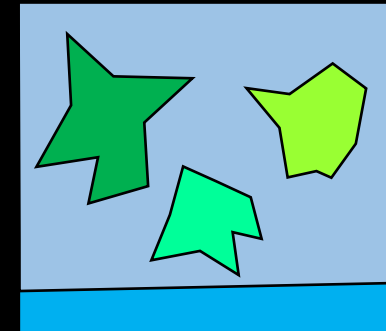
1) Ice-ocean interface



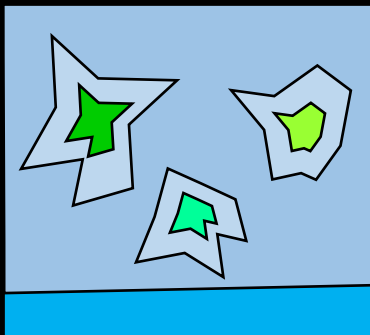
2) Freezing front advances



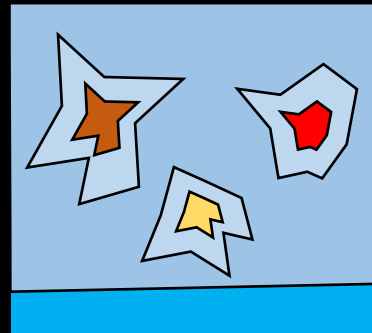
3) Ice crystals trap near surface materials



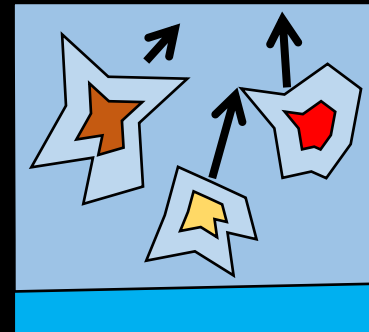
4) Material entombed in growing ice structure



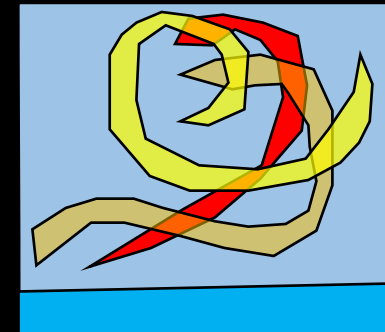
5) Water freezes out; jacks concentration



6) Chemistry happens?



7) Convective transport



8) Wonderful mixing during convection

100 km – 395 km Deep subsurface Ocean

Water Ocean

Composition 0-3% $\text{NH}_3/\text{H}_2\text{O}$ – 0-10% $\text{MgSO}_4/\text{H}_2\text{O}$
Exact depth to Ocean 74-108 km from Cassini-Huygens

$T = 261 \text{ K} - 272 \text{ K}$ shallow thermal gradient

$P = 133 \text{ MPa} - 600 \text{ MPa}$

Density: $1.1 \text{ g/cm}^3 - 1.2 \text{ g/cm}^3$

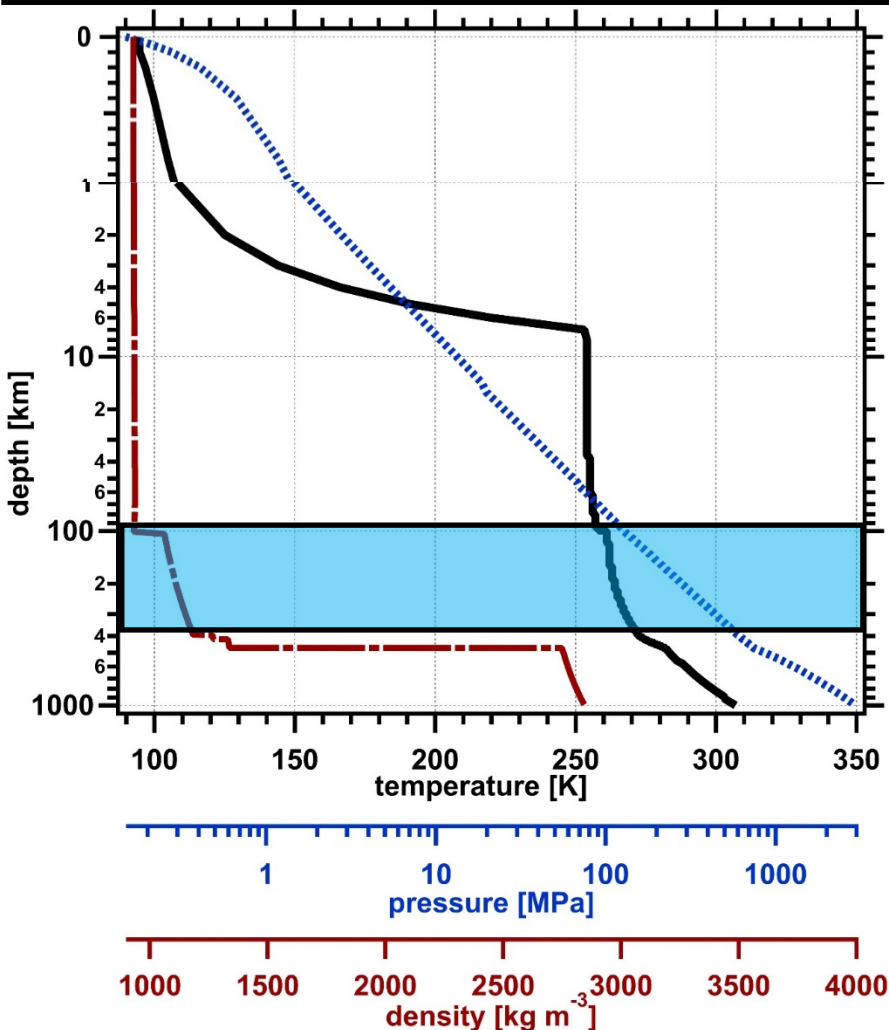
Water ocean!

Reducing conditions (oxidizing relative to the surface?)

Interfaces of ice layers (and core?)

Potential for salts extracted from core mixing

Repository for transported organics



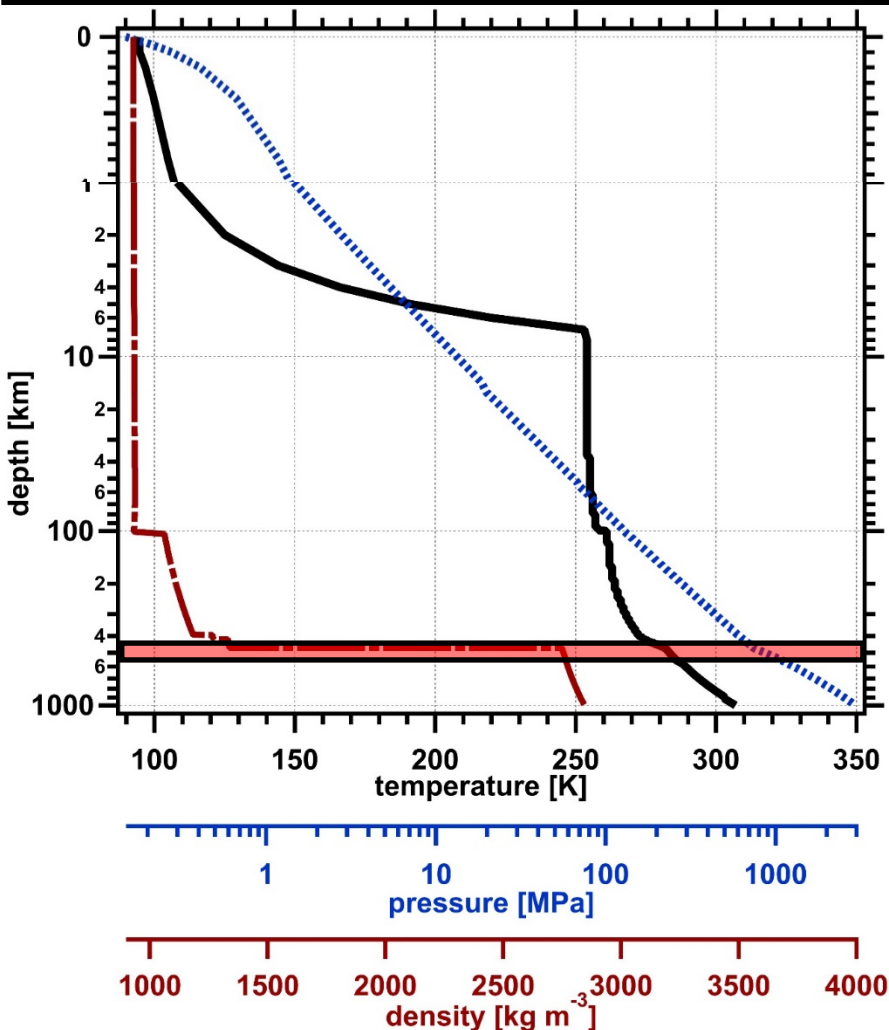
Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Key questions:

Exactly how deep to ocean?

What are likely chemical compositions?

395 km – 470 km High Pressure Ice Layers



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

HP ices (ice V and Ice VI)

May not completely seal off core from Ocean
(buoyant melts likely; Kalousova and Sotin 2018)
Layer thicknesses depend on ocean composition
and heat input

T = 272 K – 282 K shallow thermal gradient

P = 600 MPa – 750 MPa

Density: 1.3 g/cm³

Freezing conditions (squeezing ocean from both sides)
may allow similar jacking of trapped chemicals

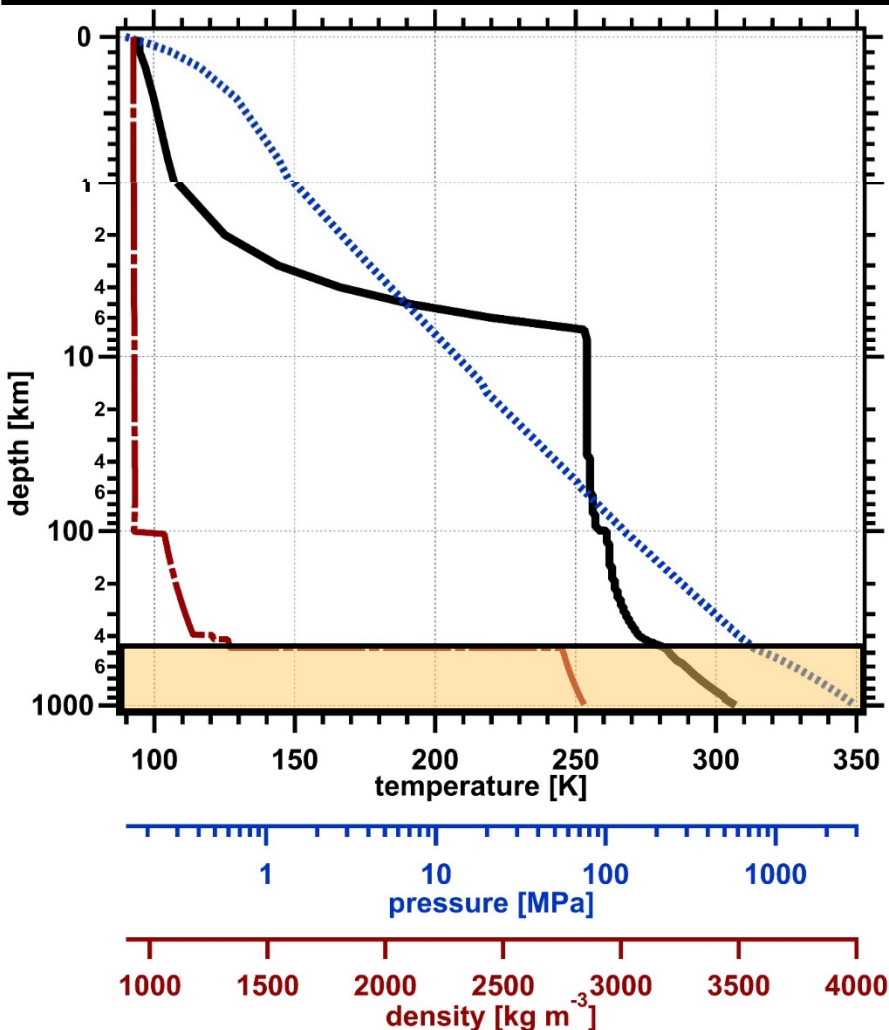
Key questions:

Exactly how deep to the ocean?

What are likely chemical compositions?

470 km – center Hydrated silica core

Hydrated silicates



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

$T = 282 \text{ K} - 340 \text{ K}$ (500 K?) shallow thermal gradient
 $P = 750 \text{ MPa} - 9.9 \text{ GPa}$ (Earth life limit is 2.1 GPa)
Density: $2.7 - 3.2 \text{ g/cm}^3$

Possible inhomogeneities could create diverse microenvironments in core and contact with HP ice

Primarily inorganic environment

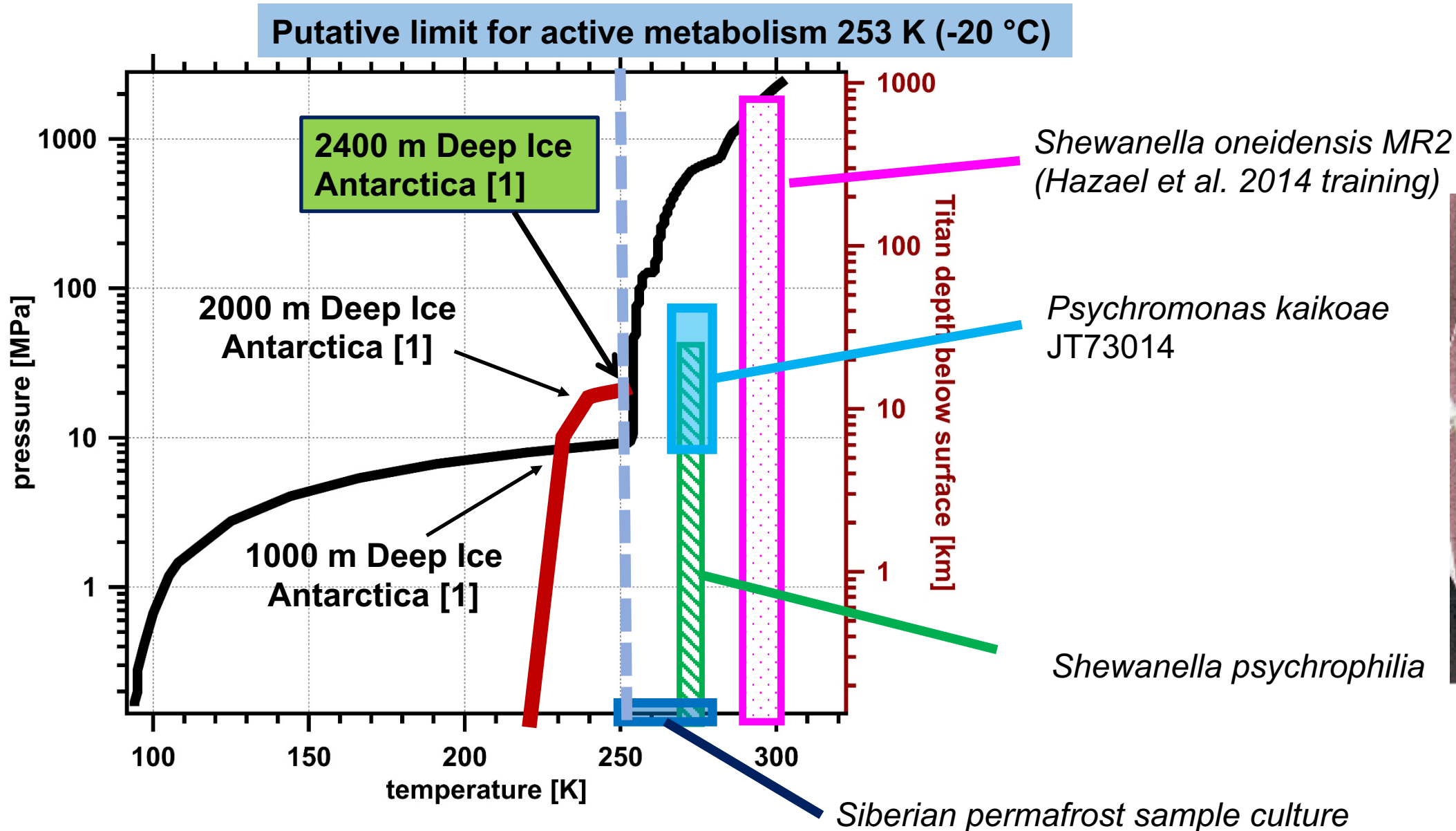
Source of CH_4 , NH_3 , and organics! (Miller et al. 2019)

In theory, life could exist to 2000 km depth at Titan pressure, temperature conditions.

Key questions:

How much exchange with Ocean now? In past?
Pore spaces/fracture/fluid convection?
What are high-pressure limits for terrestrial life?

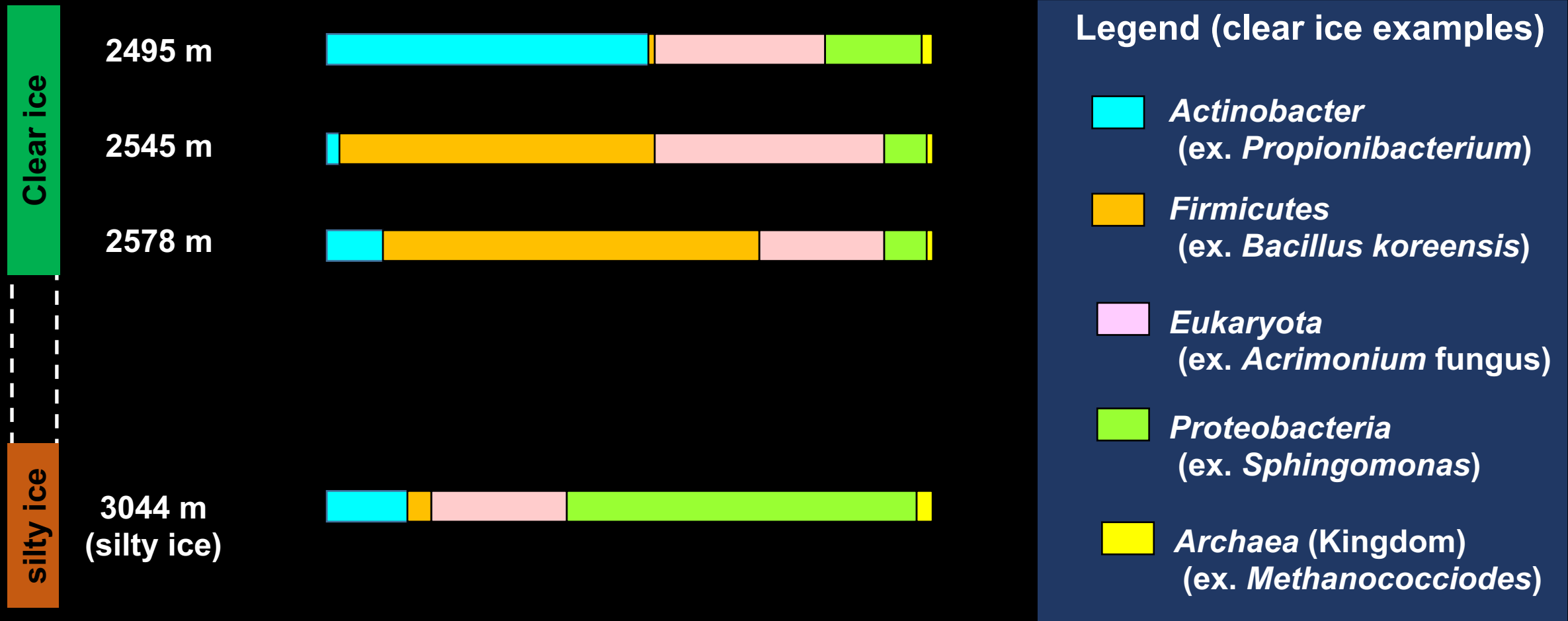
Titan P,T plot overlaps with terrestrial Deep Ice habitats!



Microbial diversity in terrestrial Deep Ice

Data from GISP2 core melt and culture experiments

Corresponding *P.T* conditions of 11 km deep in Titan' subsurface



Titan's Layers: Conclusions, Implications, and Questions

Multiple layers of Titan; Multiple opportunities to mix organics / water

How deep do organics go down from surface?

Or come up from interior?

Some Titan conditions similar to conditions in Antarctic/Greenland Deep Ice environments

Convective ice layer (7 km - 100 km) and crustal ice ocean interface (100 km) might be most favorable for life to exist, and even originate on Titan.

Large areas of habitable T and P (and some liquid H_2O) could exist on Titan
Need a combo psychrophile-piezophile

What are the cold-pressure combination limits of adapted terrestrial life?

What are further constraints on physical/chemical environment?

What are transport mechanisms/fluxes?